LUMEN DEMONSTRATOR – PROJECT OVERVIEW

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ABSTRACT:

The DLR project LUMEN (liquid upper stage demonstrator engine) aims at developing and operating a modular LOX/LNG bread-board engine in the 25 kN thrust class for operation at the new P8.3 test facility in Lampoldshausen[1, 2]. The main focus of this project is to strengthen DLR's competence on rocket engine system level as well as to enable tests of new components in a representative system environment. This article gives an overview of the background of the LUMEN project. The planned bread-board engine is described and the reasoning behind propellant selection, choice of the expander-bleed scheme as the engine cycle layout and selection of technologies for key engine components is explained.

1. LUMEN PROJECT: BACKGROUND AND MOTIVATION

DLRs Institute of Space Propulsion has a long-standing heritage of experimental research related to aspects of rocket engine thrust chamber design. Due to the traditional focus on LOX/hydrogen propulsion systems in Europe, such as Vulcain, HM-7B or Vinci, the scientific focus was consequently placed on high pressure combustion phenomena of LOX and hydrogen. The scientific fields of interest included topics such as ignition and transients, combustion efficiency and dynamics and injector design, combustion chamber cooling, nozzle flow as well as thrust chamber structures and fatigue life.

Experiments related to high pressure combustion were conducted with a wide variety of test specimen at the European research and development test bench P8, which offers the possibility to test at conditions representative of typical rocket engines [3]. Since 2014, DLR is also building up competences in the field of turbomachinery.

Based on these existing competences and test capabilities, DLR initiated the LUMEN breadboard engine project in 2017 with the following main goals:

- Advancing the understanding of engine processes at a system level
- Demonstrating the ability to predict the behaviour of whole engine cycles
- Linking of competences in engine component design existing at DLR
- Advancing the organizational ability to conduct engine demonstrator projects in a research focused environment
- Providing a modular test bed for investigations of new components and engine cycle layouts in later project stages

These goals were to be achieved by designing, manufacturing and testing a liquid rocket engine demonstrator in a test bench environment.

Although engine component design competence is a prerequisite for such a project, the experience gained during the design process of a complete engine cycle with its strong interactions is also benefitting the already existing design competence on component level. Joining existing component competence to enable the design of a complete engine cycle is also helping to focus the research effort on critical aspects of each component. Additionally, the final LUMEN breadboard will serve as a test vehicle for new engine component technologies, which can then be tested at engine system level. Those two aspects will greatly benefit rocket engine component design competence at DLR.

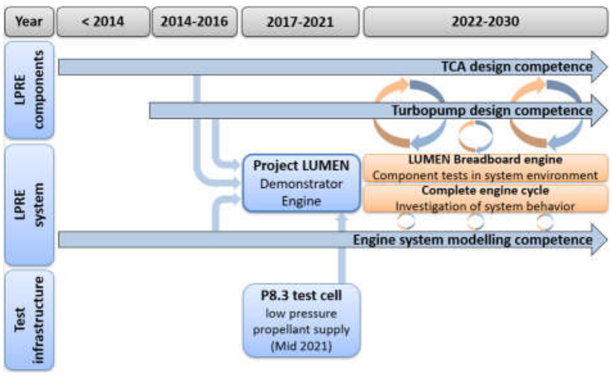

Figure 1. Project LUMEN in the framework of past and current research activities at DLR

The project was initiated as an internal DLR project, with no participation of industrial partners and other agencies. In total four DLR institutes are part of the LUMEN project. The necessary funding is provided entirely by DLR.

To limit development and operating costs, the demonstrator scale was limited to the capabilities of the P8 test facility. Since the existing supply system of the P8 test facility with its two test cells (P8.1 and P8.2) is designed for a high-pressure propellant supply, it is not well suited for the low pressure, large pipe diameter propellant supply needed for full engine demonstrators. To accommodate the LUMEN breadboard engine as well as similar test specimen, a new test cell for a low-pressure propellant supply of engines with a maximum thrust level of 75 kN is currently under construction. It is expected to enter service by mid-2021. This new test cell is directly linked to the existing P8 facility, is using part of its fluid as well as measurement and control systems and will be operated under the designation P8.3 [1].

Similar projects are pursued at several agencies worldwide. In Europe, the French agency CNES is developing the BOREAS demonstrator together with national industry, which is also to be tested at the P8.3 test position [4]. This LOX/H_2 based, expander bleed cycle demonstrator in the 10 kN-class is dedicated to developing engine component technologies in a system environment. The Italian agency CIRA is pursuing the HYPROB project based on the propellant combination LOX/CH_4 [5]. In Japan, the LOX/H_2 based RSR engine represents a very similar approach [6]. Another Japanese Project demonstrator project is conducted by JAXA and IHI to support the development of future LOX/methane engines [7].

The LUMEN breadboard engine project is intended to provide an experimental platform open to partners from the institutional as well as the industrial domain. Its focus on a modular design with an emphasis on a high level of instrumentation offers the possibility to test thrust chamber, turbopump or other engine components in a truly representative environment. The LUMEN demonstrator will be operated as a test facility on its own, to be used in conjunction with the P8.3 test facility and open to potential partners.

2. LUMEN DEMONSTRATOR DEFINITION

2.1. Demonstrator requirements

The design of the LUMEN breadboard engine is focusing on the demonstration of a complete engine cycle. Its envisaged operation in a research centred environment calls for a high level of modularity, easy sensor implementation and a high number of potential operating cycles. Primary requirements for the demonstrator are therefore:

- Stable operation at the design point (see paragraph 2.3)
- High representativity in terms of the thermodynamical behaviour of individual components and the entire engine cycle
- High level of modularity and accessibility
- High number of operating cycles for as many components as possible
- Low costs for manufacturing and operation

The following requirements are considered to be of secondary nature. They are to be achieved only if doing so would not jeopardize the primary requirements mentioned above:

- High specific impulse
- Demonstration of large throttling range (see paragraph 2.3)
- Full representativity in terms of the transient behaviour of individual components or the entire engine cycle

Most importantly, due to LUMEN being only a test bench breadboard engine, the following aspects are out of scope for this project:

- Compliance to flight application requirements (e.g. propellant supply pressures)
- Compliance to a maximum weight constraint
- Compliance to a maximum space constraint

2.2. Propellant and thrust level selection

The propellant combination choice for the LUMEN demonstrator was based on a trade-off analysis considering aspects such as existing technological heritage and test capabilities at DLR, current developments regarding future European engines as well as financial and technical risks associated with different possible engine cycle variants. This trade-off analysis showed that the most promising propellant combination for the LUMEN demonstrator is LOX/methane.

Historically, research at the Institute of Space Propulsion was directed towards a better understanding of thrust chamber processes in LOX/LH_2 fuelled applications like the European engines Vulcain, Vinci and HM7-B. A vast body of experimental data regarding all aspects of LOX/LH_2 combustion and thrust chamber operation was accumulated over more than 20 years of continuous research at test facilities like the P8 test bench. Since the early 2000s, LOX/methane was investigated in detail as well. Still, certain critical aspects of LOX/methane thrust chamber design remain challenging, e.g. control of LOX/methane ignition and flame holding processes and operation of cooling channels with methane at sub- and trans-critical conditions. In terms of availability, both propellant combinations are regularly employed at DLRs sub-scale research test benches. The possibility to test with LH_2 or LNG is also foreseen at the future P8.3 test facility.

Since 2015 the European space industry is developing a new 100-ton class LOX/LNG pre-cursor engine for main and upper stage applications: Prometheus [8]. To support this development effort, DLR is intensifying its scientific work on LOX/LNG related topics. This includes the development and maturation of technologies specifically for LOX/LNG engine applications. With the LUMEN demonstrator being the integration

platform for these new technologies matured at DLR, LOX/LNG is the natural choice for the propellant combination of this demonstrator to support the planned shift towards LOX/LNG.
A critical part of the trade-off between LOX/LH_2 and LOX/LNG are the financial and technical risks involved in such an engine demonstrator project. Technical risks were assessed for each major building block: thrust chamber assembly, turbopumps and supporting fluid control components like valves. Major aspects of thrust chamber operation with LOX/LH_2 are quite well understood. These include the injection and ignition processes, chamber wall heat transfer and regenerative cooling with LH2. The technological risks were considered comparably low in this case. Operation of a similar sized combustor with LOX/LNG introduces some additional technical challenges:

- Ignition
  LOX/LNG exhibits a smaller ROF range for reliable ignition than LOX/LH_2 [9]. The ignition transient therefore needs to be controlled more carefully.
- Combustion
  Compared to LOX/LH_2, a LOX/LNG reaction is by far slower to reach an equilibrium state. The reduced flame speed leads to less stable reaction zones, which are more susceptible to extinction by shear. This has to be considered for the design of injector elements. The same phenomenon is probably also responsible for the increased tendency towards combustion instability observed for LOX/LNG applications.
- Cooling
  The fluid properties of the coolant in the cooling channels approach the critical point of methane/LNG and even cross the Widom-line in many cases. This leads to heat flux deterioration effects, which need to be considered for a suitable cooling channel design [10] [11]. This aspect is even more important considering the choice of the thermodynamic engine cycle for the demonstrator (expander-bleed, see paragraph 2.4). As a possible solution to this problem, Machine Learning (ML) methods offer the possibility to integrate more accurate CFD-calculation in system studies in the early design phase [12].
- Modelling
  The chemical composition of LNG requires the use of complex reaction schemes for the numerical treatment of combustion chamber processes. Detailed numerical investigations of combustion processes involving LOX/LNG are extremely costly in terms of computational power.

On the other hand, the use of LOX/LNG significantly reduces development risks for turbopumps. The propellant density directly affects the rotational speed and the necessary number of impeller stages of a pump. Therefore, the low density of LH_2 leads to increased requirements for a turbopump compared to the LNG case. Typical rotational speeds range from 36 000 rpm (Vulcain) to 90 000 rpm (Vinci). The density of LNG differs only by a factor of 2 from that of LOX, allowing for pumps with similar rotational speeds. An LNG battleship turbopump was considered to be associated with far less technical challenges than a comparable LH_2 unit.

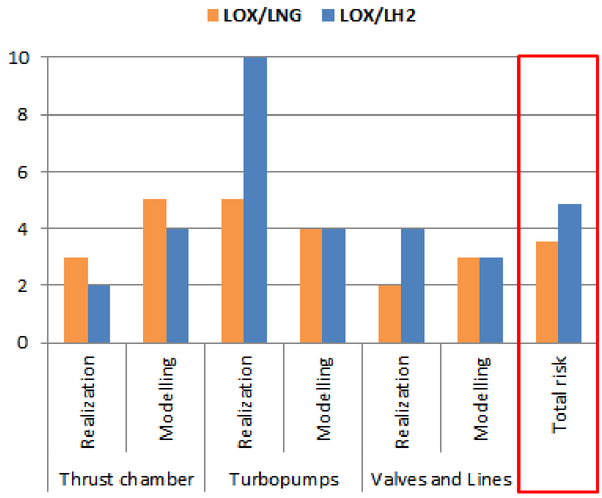

Figure 2. Risk trade-off between LOX/LNG and LOX/LH_2.

The resulting risk assessment based on these technological aspects is graphically illustrated in Figure 2. Considering this preliminary risk assessment as well as other aspects such as existing technological heritage at DLR and current developments in Europe like Prometheus, LOX/LNG was chosen as the propellant combination for the LUMEN demonstrator.
The demonstrator scaling in terms of thrust level was the result of a similar trade-off considering aspects such as:

- Available test facilities and their mass flow and thrust restrictions
- Possible test duration with given test bench tank volumes
- Use of existing heritage for certain scales
- Manufacturing costs
- Possible technological risks resulting from too large or too small individual components

The demonstrator design has to be compliant to the mass flow and thrust range of the P8.3 test facility. This test facility offers the possibility to operate LOX/LH_2 or LOX/LNG engines with thrusts up to 75 kN. The resulting propellant consumption at 75 kN thrust level on the other hand leads to shorter test durations with less operating conditions to be investigated per test day. A smaller scale is therefore more economic from a scientific point of view. Consequently, a thrust level of about 25 kN was considered optimum for the intended purpose of the LUMEN demonstrator. To be representative for typical upper stage engines, a combustion chamber pressure of 60 bar at the nominal thrust level was selected.

2.3. Operational domain

One of the design goals of the LUMEN engine is the demonstration of a large throttling range. For the chosen propellant combination of LOX/LNG, the LUMEN nominal load point is set to a combustion chamber pressure of p_{CC} = 60 bar and a mixture ratio of ROF = 3.4. The planned operational domain is summarized in Table 1. These pressures result in a throttling range of about 58% to 133% of nominal thrust.

Table 1. Operational domain of the LUMEN combustion chamber

	Nom.	Max.	Min.
Chamber pressure / bar	60	80	35
Chamber fuel mixture ratio	3.4	3.0	3.8

2.4. Engine architecture

The engine cycle selection for the LUMEN demonstrator was driven by following considerations:

- Similarity to typical upper stage engine cycles
- Reduction of technical risks
- Reduction of costs
- Specific impulse as only a secondary requirement

Four typical engine cycle configurations used in flight engines were under consideration: two closed scheme cycles, with and without pre-burner (staged combustion and expander cycle) and two open scheme cycles, again with and without pre-burner (gas generator and expander bleed cycle).
The requirement of close similarity to a typical upper stage application rules out the use of a complex and heavy staged combustion cycle scheme. The remaining closed scheme cycle, the full expander cycle, was ruled out since open scheme cycles offer more possibilities for tuning of the operational points of the cycle due the bleed mass flow used to drive the turbines. This decision was made to reduce the technical risks for the realization of the demonstrator engine.
The final trade-off between the open cycle schemes (gas generator and expander bleed) was performed on the basis of general risk reduction and cost reduction in terms of development costs. In the case of a gas generator cycle, an additional combustion device needs to be developed. This adds the technological challenge of operating a LOX/LNG combustion device at very low mixture ratios, an operational regime which is prone to flame extinction events and occurrence of combustion instability. Therefore, the option gas generator was discarded in favour of a less complex expander bleed cycle.
After selection of the expander bleed scheme as the general cycle layout, some design choices remain. Again, these design options were chosen with the requirement of risk and cost reduction in mind.

- Turbopump design and arrangement
  For the chosen propellant combination of LOX/LNG, a typical design choice for a flight application would be the use of a single-shaft turbopump with LOX and LNG pump on a common shaft driven by a single turbine. This arrangement minimizes size and weight of the turbopump unit while at the same time calls for design compromise between both pumps since they need to run at a common rotational speed. For the LUMEN demonstrator two separate turbopump units are foreseen, which can be optimized individually. At the same time, this approach increases the flexibility of operation of the LUMEN demonstrator.
  The arrangement of the two turbopump units was chosen to be parallel. This arrangement allows for the development of very similar turbines with identical, but rather high pressure ratios (reduction of development costs) and it allows for a simple control of available power for each turbopump.
- Chamber or nozzle expander bleed
  A nozzle expander bleed (NEB) layout was chosen to allow for a maximum heat pickup for the cycle [13].
- Fuel injection temperature
  To provide a fixed and controlled propellant inlet temperature at the injector, a fuel mixing system will be employed, which remixes part of the heated fuel from the cooling channel with the main cold fuel mass flow. The same principle is applied in Japanese expander bleed engines like LE-5B.
- Control
  In contrast to flight-like engines, the LUMEN demonstrator as a research platform is supposed to offer a maximum amount of possibilities for regulation. To allow for changes in the cycle behaviour during testing, regulation valves are used at multiple positions instead of orifice solutions. The large number of control valves calls for new approaches for the control strategy of the system. New data-based control schemes offer interesting possibilities here [14].

Figure 3 shows a schematic representation of the LUMEN engine cycle, which incorporates the general design features mentioned above. The LUMEN breadboard demonstrator is following an expander bleed engine cycle scheme. The combustion chamber is cooled with LNG in a counter-flow arrangement. The heated cooling fluid is partially remixed into the main fuel mass flow to actively control the fuel injection temperature. The remaining cooling mass flow is further heated within the nozzle extension (co-flow arrangement) and then divided between the LOX and LNG turbines. The demonstrator architecture also includes a number of purge valves for pre-conditioning of the system using LN_2, which are not shown in Figure 3 for simplicity. An external GN_2 supply will also be used as a turbine starter system to accelerate the engine start-up transient.

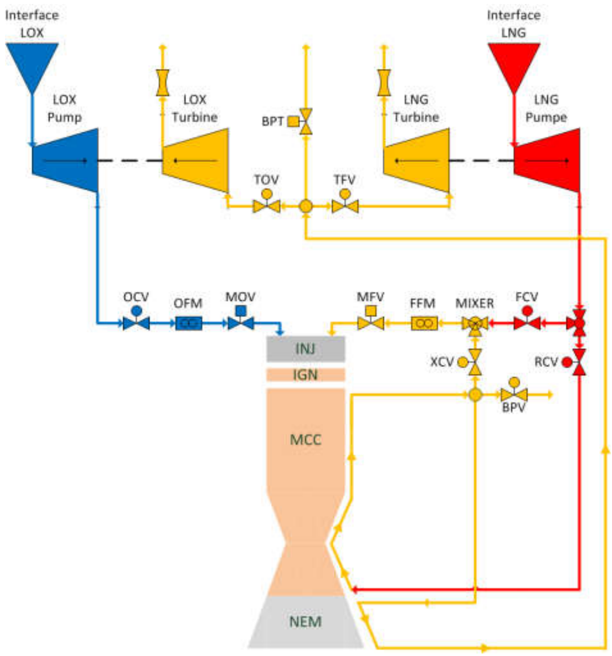

Figure 3. Schematic representation of the LUMEN demonstrator architecture.

The cycle features two bypass valves. The turbine bypass is designed as a fast-acting security valve, which allows for a rapid reduction of turbine power in case of an emergency shut down. The second bypass is designed as a regulatory valve, which allows controlling the amount of LNG mass flow to be further heated within the nozzle extension. This measure is needed if the fuel mass flow for combustion chamber cooling is larger than the combined mass flow needed for remixing and operation of the turbines. In this case, the bleed mass flow can be adjusted to the need of the turbine and the heat addition in the nozzle extension is resulting in the maximum temperature increase of the bleed mass flow. From a performance point of view, this bypass should be zero. However, the large surface area to volume ratio of the chamber and the cooling properties of methane in some operating points necessitate a larger cooling fluid mass flow than the combined need of combustion chamber fuel mass flow and turbine bleed mass flow.

The large number of fluid control elements allows for several options for the operation of the cycle. One option for example is the independent control of combustion chamber and cooling channel pressure. This option allows for super-critical conditions within the cooling channels while operating the combustion chamber at sub-critical conditions.

To allow for a maximum degree of accessibility for instrumentation, the LUMEN demonstrator is designed with a lot of space between components. Figure 4 shows the current layout of the LUMEN demonstrator engine as it will be tested at the P8.3 test facility.

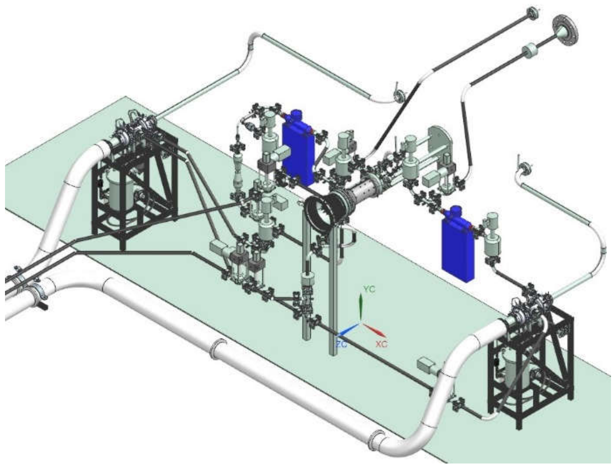

Figure 4. LUMEN demonstrator engine layout

3. ENGINE COMPONENT DESIGN

The requirements for the design of the LUMEN breadboard components were derived from the high-level requirements for the demonstrator and first iterations of cycle analysis for the entire cycle.

3.1. Thrust chamber assembly

A number of key requirements for the design of the thrust chamber components at nominal operating conditions are listed in the following:

- General thrust chamber propellant inlet conditions
  - LOX: $\dot{m}$ = 5:946 kg/s, T_{Inj} = 98 K
  - LNG: $\dot{m}$ = 1:749 kg/s, T_{Inj} = 215 K
- Igniter
  - Integration in combustion chamber liner or separate igniter ring
  - No active cooling of igniter ring
  - No pyrotechnical or hypergolic igniter
  - Possibility of 4 re-ignitions
- Injector
  - Operation with gaseous or super-critical fuel inlet conditions
  - Combustion efficiency η_{c*} = 95 % at nominal operating conditions
  - Stable combustion with a maximum combustion roughness of p' = 2:5 % at nominal operating conditions
- Combustion chamber
  - Cylindrical chamber diameter d_{CC} = 80 mm
  - Contraction ratio ε_c = 2.3
  - Regenerative counter-flowing cooling circuit

- Maximum wall temperature T_{wall} = 900 K
- Cooling fluid temperature increase of ΔT > 300 K
- Cooling fluid pressure drop of Δp < 20 bar

- Nozzle extension
  - No flow separation at nominal operating conditions (60 bar)
  - Regenerative co-flowing cooling circuit
  - Maximum wall temperature T_{wall} = 1000 K
  - Cooling fluid temperature increase of ΔT > 50 K
  - Cooling fluid pressure drop of Δp < 5 bar

Due to the existing heritage at DLR a classical shear-coaxial injector was chosen and tested for LOX/LNG [15] [16].
To allow for the requested number of re-ignitions during a single test run, a laser plasma igniter was selected as the baseline solution for the ignition system. DLR has acquired an extensive data base regarding the ignition of shear-coaxial type injectors with LOX/H2 and LOX/CH4. The associated technological risk is therefore considered to be low. Nevertheless, a high-pressure LOX/H2 torch igniter is foreseen as a backup solution. The details of the igniter layout are given by [17].
The combustion chamber features an inner CuCrZr liner with axially milled cooling channel. The cooling channels are closed by copper electro-plating and an outer nickel shell. The main challenge for the combustion chamber design is resulting from the cooling properties of methane. The maximum allowable hot gas side wall temperature has to be guaranteed considering the heat flux deterioration effect of methane close to the Widom line [10] [11]. Crossing of the Widom line does occur at different positions in the cooling channel for different operating conditions. The cooling channel flow field was evaluated by CFD for the nominal and throttled operating conditions to guarantee sufficient heat pickup for the operation of the turbines as well as combustion chamber wall temperatures not exceeding the given temperature limit [18]. The following nozzle extension will be manufactured by ALM from Inconel718 powder. Cooling of this component will be provided by conventional cooling channels.

3.2. Turbopump

The turbopump units are expected to provide the needed pressure head and volumetric flow rate for each propellant at nominal and throttled operating conditions. Few additional functional or design requirements were imposed on the turbopump components to exclude as few design choices as possible. The required pressure rises are given for the nominal conditions in the following:

- LOX turbopump (TPO)
  - Compatibility with LOX inlet temperature of T = 91 K
  - Pressure rise of $\Delta p \approx$ 85 bar at nominal operating conditions
- LNG turbopump (TPF)
  - Compatibility with LNG inlet temperature of T = 114 K
  - Pressure rise of $\Delta p \approx$ 100 bar at nominal operating Conditions

The resulting design of the turbopump units is focused on reduction of technological risks. Both turbopumps are designed as modular devices based on a common central bearing block with pump and turbine section mounted on the overarching shaft. The central bearing block contains four bearings in two pairs. Lubrication is provided by oil, therefore enabling long service life even with COTS bearings. The LOX and LNG pump are designed as inducer-less, single stage impellers. The inducer components were omitted for this first turbopump design to eliminate the risk of contact between inducer and wall. This design option is available since the risk of cavitation can be eliminated by raising the P8.3 interface pressure to more than 7 bar.
The turbines are designed as partially loaded, single stage impulse turbines. Partial admission is provided by a discrete number of round stator nozzles.
Detailed information regarding the development and testing of the LUMEN turbopumps is given in [19] [20] [21] [22].

4. PROJECT TIMELINE AND DEVELOPMENT STATUS

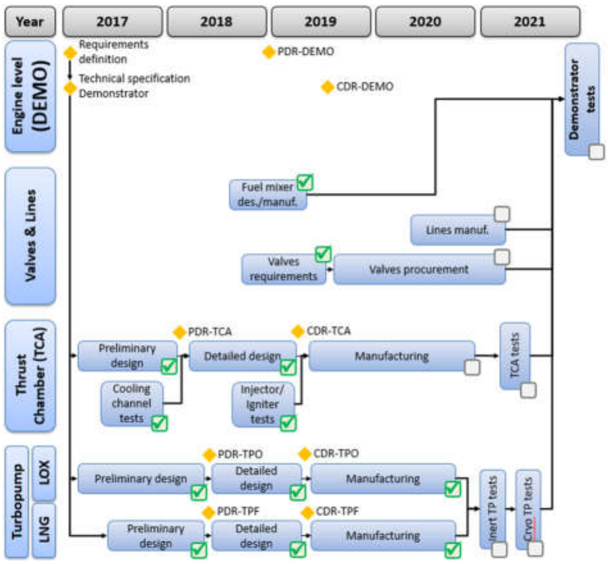

Figure 5. Current schedule and status of development for the LUMEN

The project LUMEN was started in 2017 and is planned to finish with a successful hot run of the integrated demonstrator by the end of 2021. The general project outline and major activities are shown in Figure 5. Similar to other projects, the progress of LUMEN was heavily influenced by the corona pandemic. The pandemic and the

subsequent lock-down had a major influence on the available test slots as well as on manufacturing and procurement processes. Consequently, the project schedule needed to be adapted to account for these delays.
First project milestones were the requirement definition for the entire demonstrator and the technical specification on engine level in early 2017. Based on these high-level requirements the functional specifications of the subcomponents were derived and the preliminary design phase was started. Thrust chamber and turbomachinery reached PDR status in 2018. LUMEN successfully passed the PDR on engine level in the beginning of 2019.
Current activities focus on final assembly of both turbopump units as well as the preparation of the concluding test campaigns.

5. OUTLOOK

Upcoming activities within the LUMEN project include:

- Thrust chamber hot fire tests
  The integrated LUMEN thrust chamber will be tested on the P8.2 test bench by mid-2021. The tested specimen will be the same as the one that will be used for the integrated engine tests by the end of 2021. The main goals of this test campaign are the demonstration of a) stable combustion at all load points specified, b) the expected combustion efficiency and c) the predicted heat flux to the cooling fluid. The test data will be used to further anchor the system analysis tools in preparation for the integrated demonstrator tests.
- Turbopump testing
  Following final integration of both turbopump units, tests with simulation media are planned to verify the performance predictions. Again, this test data is highly valuable for the demonstrator test sequence development.
- LUMEN demonstrator test campaign preparation
  The data gathered by testing of both thrust chamber and turbopumps as well as other fluid control elements like valves will serve as a basis for the prediction of the operational behaviour of the integrated engine cycle. Considering the transient behaviour of those core components, the critical transients (chill-down, start-up and shutdown) will be developed numerically using the EcosimPro/ESPSS environment.

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